

Dispersal of Fine Sediment in the Coastal Ocean: Sensitivity to Aggregation and Stratification

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LONG-TERM GOALS

By improving numerical representations of coastal circulation, sediment properties, and waves, we seek to develop reliable estimates of sediment concentration, transport and deposition. Efforts to include sediment transport calculations within three-dimensional numerical hydrodynamic models can increase our ability to predict suspended sediment concentrations, water column turbidity, and seabed characteristics. Predicting the dispersal of fine grained material (silts and clays) is especially critical, because they often dominate fluvial input to the coastal ocean, and control light attenuation and backscatter there. Transport of fines is difficult to predict, however, because their hydrodynamic properties vary in response to bed consolidation and repackaging as particle aggregates. Calculations of sediment concentrations are extremely sensitive to the settling velocity of such particles, which can vary over an order of magnitude, depending on aggregate size and density. The vertical dispersal of particles also responds to stratification induced by concentration gradients of suspended sediments, which is usually neglected or poorly resolved in three-dimensional models.

OBJECTIVES

High resolution, one-dimensional numerical models have shown some success in accounting for bed consolidation and stratification (see, for example, Styles and Glenn, 2000; Traykovski et al., 2007; Wiberg et al., 1994). These processes, however, are nearly always neglected in three-dimensional sediment transport models. Additionally, consensus has not been reached as to the best way to account for aggregation and disaggregation within three-dimensional sediment models. We are working to account for aggregation and disaggregation processes, and near-bed stratification within the Regional Ocean Modeling System (ROMS) framework (see Haidvogel et al., 2008; Shchepetkin and McWilliams, 2005). Data available from the Adriatic Sea, and other field studies may provide diverse test beds for the calculations. Research products would include flocculation and stratification routines that could be implemented within three-dimensional numerical models, and which could then be applied and tested in coastal oceans worldwide.

I have again worked on the sediment stratification problem in this funding year. Comparisons between a high-resolution, one-dimensional model and field data indicate that sediment induced stratification within the wave-boundary layer is critical for estimating sediment concentrations and fluxes

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(Traykovski et al., 2007). Additionally, our own comparisons between the numerical model and field data indicate that the three-dimensional model overestimates vertical mixing of sediment within the water column (Bever, 2006).

APPROACH

Near the seafloor, stratification due to suspended sediments occurs at vertical spatial scales (millimeters) that are unresolved by typical three-dimensional numerical models (tens of centimeters). This sub-grid scale process could conceivably be handled using two approaches: (1) parameterization of stratification at the spatial scales of interest or (2) inclusion of a high-resolution bottom boundary layer model such as that developed by Wiberg et al. (1994) or Hsu et al. (2007). Computational limits could prohibit the second approach, but this has not been fully tested. The first approach has been used to account for stratification at the top of the wave-boundary layer and proved successful at representing stratification there and cross-shelf transport of fluid muds (Harris et al., 2004; 2005).

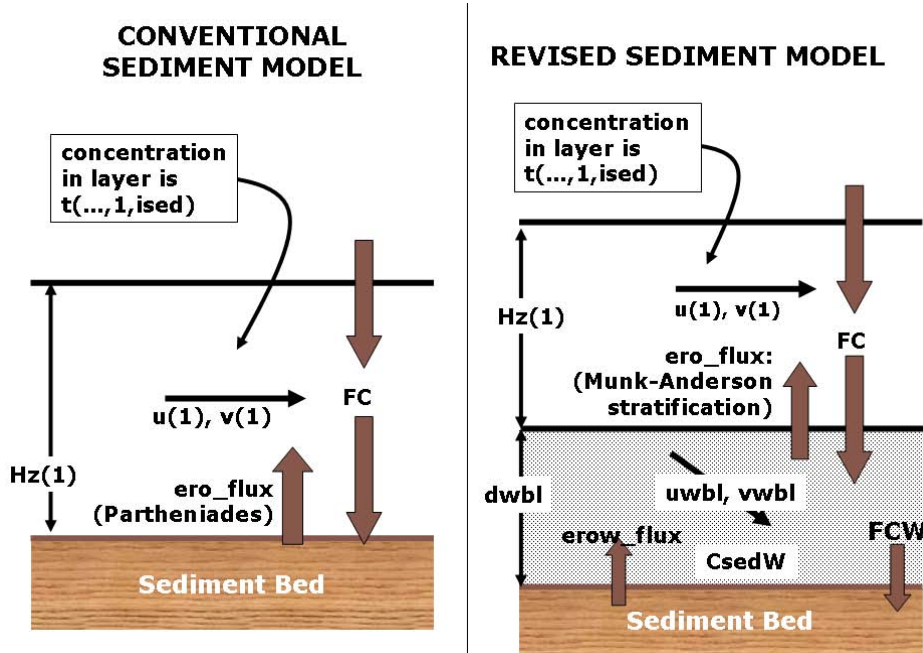


Figure 1: Left panel shows near-bed portion of the dilute suspended sediment transport model described by Warner et al. (2007) including the bottom layer of the water column grid that has thickness $H_z(1)$ and horizontal velocities $u(1)$, $v(1)$. The right panel illustrates inclusion of a near-bed wave boundary layer grid cell as described by Harris et al. (2004).

Within this funding year, we have incorporated a model similar to Harris et al. (2004) into ROMS. Work on this began last year, and has continued. Progress was slowed by a mass balance problem that was difficult to debug and correct. Figure 1 provides schematics that illustrates the conventional sediment transport model as described in Warner et al. (2007), and the framework used to include stratification at the top of the wave boundary layer. The left panel shows the conventional, dilute suspended sediment model. The bottom layer of the water column grid has thickness $H_z(1)$ and horizontal velocities $u(1)$, $v(1)$. Erosion into the layer (ero_flux) is estimated using a Partheniades relationship, and settling flux is estimated to be FC . Entrainment of sediment from the bottom layer to the overlying layer (layer 2) is based on the vertical turbulent diffusion estimated by the three-

dimensional model. The right panel illustrates inclusion of a near-bed wave boundary layer grid cell as described by Harris et al. (2004). Here, a Partheniades-type flux condition is used to estimate erosion from the seafloor into the wave boundary layer grid cell (thickness δ_{wbl} = the thickness of the wave boundary layer), and settling flux from this layer is FCW . The wave boundary layer grid cell has a horizontal velocity of u_{wbl} , v_{wbl} that depends on the density anomaly of the layer, the bathymetric slope, and drag coefficients with the seafloor and overlying water (layer 1 of the three-dimensional model). Entrainment of sediment from the wave boundary layer to the overlying water accounts for stratification across this interface following Munk and Anderson (1948).

Within ROMS, this model is being tested within a numerical test case that represents a fairly steep continental shelf (figure 2). Shelf bathymetry was based on that of the Eel River shelf, California, and spans the coastline to 200 m water depth over a 20 km wide model grid. At present, the model includes a point-source river, but the river does not supply sediment. Boundary conditions are used to specify a 5 cm/s mean alongshelf current. The initial conditions of the model include a “mud bed” between 15 – 35 m water depths that can be resuspended and transported by energetic waves and along-shelf currents. When near-bed stratification is neglected, mud will be directly entrained into dilute suspension, and transported along the shelf. Erosion would be expected at the “upstream” end of the mud bed, with deposition downstream. With the inclusion of near-bed stratification and a gravitationally driven component in the momentum equation, we would expect relatively high suspended sediment concentrations within the wave boundary layer (δ_{wbl} in figure 1) and an off-shelf directed sediment flux.

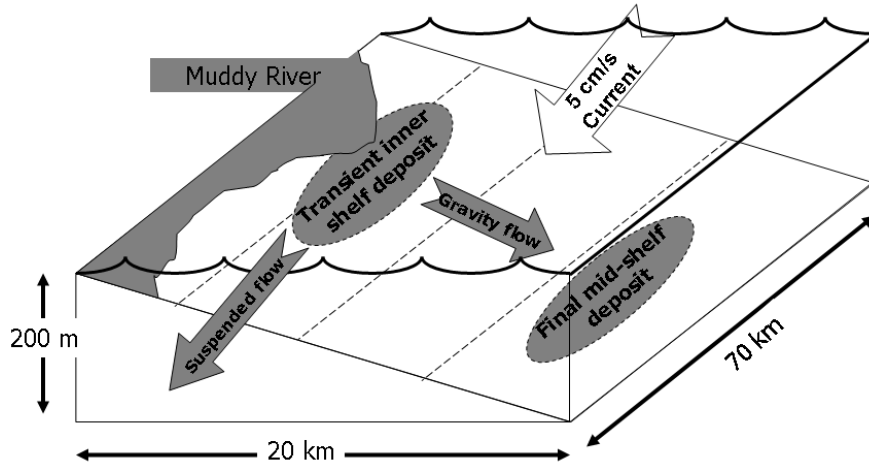


Figure 2: Test case used to represent a steep, energetic continental shelf. Model scenario includes an initial inner shelf mud deposit, and resuspension by a 5 cm/s alongshelf current and energetic waves. Later versions may include flood deposition from a muddy river.

Longer range plans for this model include comparison with higher resolution models and application to steep, sediment-rich environments, possibly including the Waipaoa River shelf, New Zealand. Also, researchers funded by the National Science Foundation (T. Kniskern and J. Warrick, USGS / UC Santa Cruz) would like to use this model to evaluate sedimentation and carbon cycling offshore of several rivers on the US Pacific coast. I plan to compare estimates made by this model to higher resolution models developed by Wiberg et al. (1994) and Hsu et al. (2007). Such intercomparisons between models promises to either refine or justify model parameters chosen by Harris et al. (2004; 2005).

Alternatively, if the model comparisons indicate that the wave boundary layer model used does not capture the relevant physics, then effort should be expended to incorporate a high resolution bottom boundary layer model (such as Wiberg et al., 1994) as a subroutine within three-dimensional models. The model neglects the drag force created by wave boundary layer on velocities in the overlying water.

WORK COMPLETED

To date, the gravity flow model of Harris et al. (2004) has been incorporated into ROMS, and the continental shelf test case has been configured to include sediment transport and waves. This year we devoted considerable effort to debugging problems with the gravity flow model, and eventually found a few errors in the way we did masking and our wave boundary layer transport equation. These errors led to mass conservation problems, but recently seem to have been corrected.

Two test cases have been run; the first uses the “conventional” dilute suspension model described by Warner et al. (2008), while the second uses the gravity flow subroutine. For both of these, an initial mud bed is present on the inner shelf (15 – 35 m water depth; left panel, figure 2). Along-shelf currents are imposed at the open boundaries to be about 0.05 m/s towards the south. Waves are assumed to be uniform and steady, with a wave height of 3 m and wave period of 15 seconds. Sediment on the mud bed is assumed to be loosely consolidated, with a settling velocity that ranges from 0.1 – 1.0 mm/s. Thus far, the model has been run on a single processor, to represent 2.5 – 7 days of real-time. Results indicate that the test case is correctly configured. The model now makes reasonable estimates for sediment concentrations and velocities within the wave boundary layer, though at first glance they seem to be lower than obtained using our previous version of the model that was developed in ECOM-SED.

RESULTS

The test case behaved properly when stratification at the wave boundary layer interface was neglected, in that erosion was estimated at the upstream edge of the mud-deposit, with deposition downstream (figure 3A). Sediment was eroded from the mud bed, and suspended material was transported southward by the alongshelf current. Deposition occurred downstream and slightly offshore of the initial mud bed. Erosion for this case was fairly high, with about 5 kg/m² being removed from the upstream edges of the mud bed.

For the case that included wave boundary layer stratification and gravity flows, the depositional patterns were very different. Sediment was eroded from the inner shelf edge of the mud bed, and transported towards deeper water. Deposition occurred directly offshore of the initial mud bed, with very little deposition to the south (figure 3B). Erosion for this case was actually smaller (<5 kg/m²) than for the case that neglected wave boundary layer stratification. This is probably due to the fact that stratification limited the upward diffusion of sediment here, and the erosion rate was therefore limited by the ability of the gravitationally driven flow to transport sediment seaward. For the case neglecting wave boundary layer stratification, sediment freely diffuses upward throughout the entire bottom boundary layer, so that more sediment may be eroded in a short time.

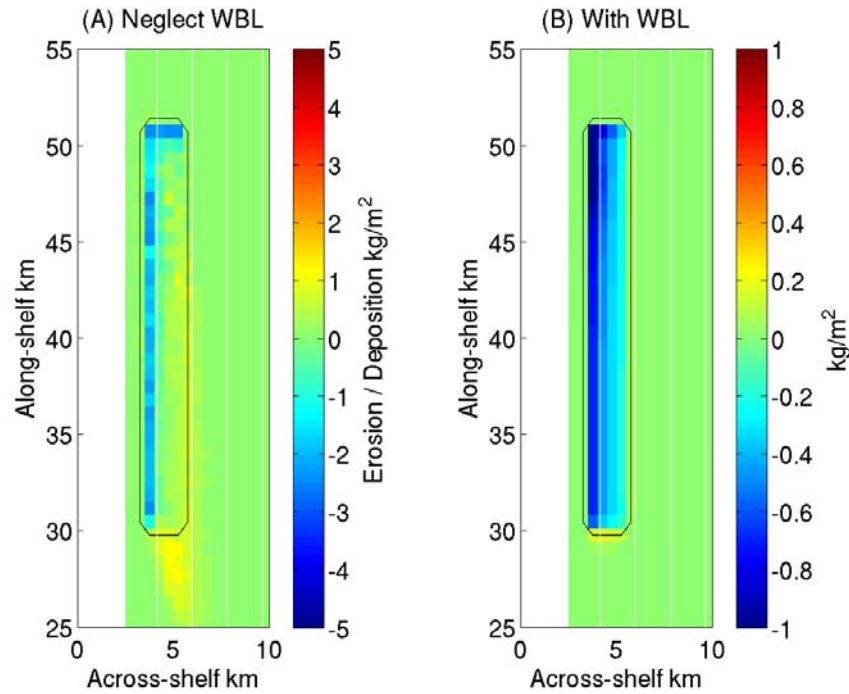


Figure 3: Net erosion (blue) and deposition (yellow) calculated for continental shelf case study when the calculations included (A) only dilute suspension; and (B) the wave boundary layer / gravity flow model. Bathymetric contours (white) drawn every 20 m. Black contour line shows initial location of 10 cm thick mud bed.

The cross-shelf structure of the wave boundary layer shows that sediment concentrations and wave boundary layer velocities increase with wave energy and sediment availability (figure 4). The thickness of the wave boundary layer for these 3m waves was estimated to decrease from about 20 cm in the inner shelf to just a few centimeters on the outer shelf. When stratification at the top of the wave boundary layer was included, concentrations there increase to be about 4 g/L (figure 4A). The stratification represented at the top of the wave boundary layer greatly inhibited upward mixing, so that concentrations in the overlying water are less than 0.5 g/L (red line, figure 4A). In contrast, the conventional model that neglected wave boundary layer stratification estimated near-bed concentrations that were twice as high as the estimates that included stratification (compare red and pink lines in figure 4). This implies that, overall; models that neglect this near bed stratification would tend to overestimate sediment concentrations and suspended sediment flux compared to models that account for wave boundary layer stratification. Velocities within the wave boundary layer were estimated to be seaward, but are presently estimated to be lower than expected (figure 4B). Because dilute suspended transport tends to be dominantly along-shelf, neglect of wave boundary layer structure and gravitationally driven flows there would likely overestimate alongshelf transport, while neglecting the dominant cross-shelf transport mechanism. Net erosion was estimated to be higher for the case that neglected wave boundary layer stratification compared to when it was included (figure 4C). Here, stratification at the top of the wave boundary layer effectively confined sediment to the wave boundary layer and limited erosion.

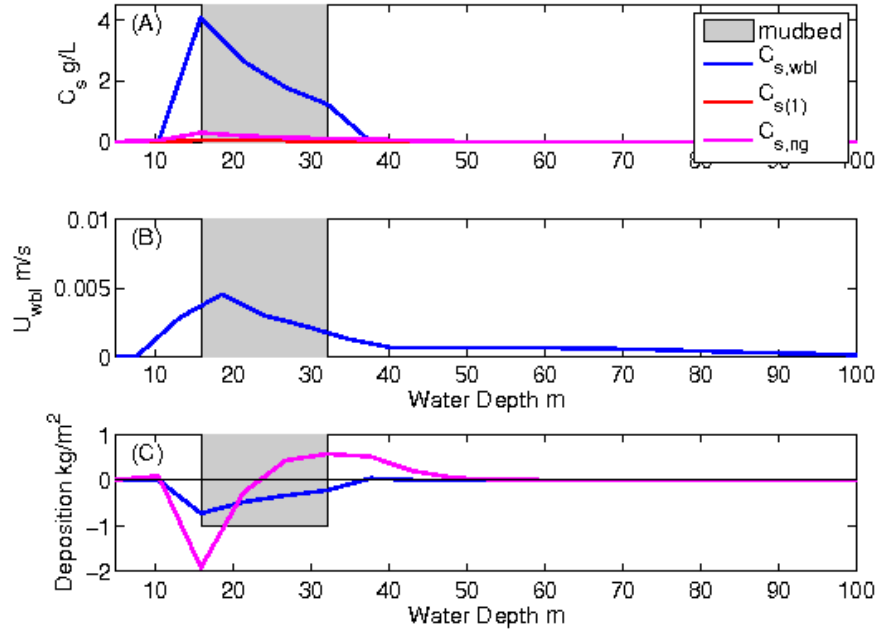


Figure 4: Calculations on an across-shelf transect. Gray boxes indicate location of mud bed. Calculations of (A) sediment concentrations within the wave boundary layer (blue) and in the overlying water (red); (B) velocity within wave boundary layer; (C) sediment erosion (<0) and deposition (>0). Magenta lines in (A) and (C) calculated neglecting wave boundary layer transport.

To summarize, the wave boundary layer model of Harris et al. (2004; 2005) that was developed to account for cross-shelf transport by near bed fluid muds is being added to the ROMS sediment code. Motivation for this stemmed from the fact that typical three dimensional sediment transport models do not represent the near bed structure of either suspended sediment concentration profiles, or of sediment flux. At present, the ROMS implementation estimates proper wave boundary layer thicknesses over a range of wave characteristics and water depths. It also produces high concentration near-bed wave boundary layers, and stratification with the overlying water column that seems similar to field observations (Traykovski et al., 2000; 2007). The model represents down slope gravity driven flow of the wave boundary layer retarded by friction with the seabed and overlying waters, and produces very different depositional patterns compared to a similar model that neglects the structure of the wave boundary layer. The sediment concentrations estimated for the wave boundary layer are higher than those estimated for the overlying water, and these two values seem to straddle the concentration estimated for the near bed region when wave boundary layer structure is neglected. Ongoing efforts are aimed at comparing this formulation to the one published in Harris et al. (2004, 2005). We will then evaluate these calculations by comparing them to higher resolution, one-dimensional models.

IMPACT/APPLICATIONS

Efforts in this project complement development of the NOPP CSTMS (Community Sediment Transport Modeling System) by filling a gap in ongoing work funded by that program. Once matured, the wave boundary layer model will be provided to CSTMS PIs, and may be fully incorporated into the CSTMS. We specifically hope to evaluate the behavior of this representation of wave-supported fluid muds through direct comparison with a higher resolution two-phase model (Hsu et al., 2007).

Communication with the CSTMS group will continue via attendance at CSTMS meetings and participation on the ROMS forum.

TRANSITIONS

Numerical models that I previously developed with the support of the ONR Coastal Geosciences program continue to be used by researchers in academic, industry, and government sectors. The Harris and Wiberg (2001) model has been used by researchers and students in Europe, Australia, Indonesia, Asia, and in the U.S. at the National Oceanic and Atmospheric Administration's (NOAA's) Great Lakes Experimental Research Laboratory (GLERL). In this funding cycle, Harris contributed to this effort via conference and journal publications (including Hawley et al., 2008). Additionally, the sediment bed routine was adopted by the NOPP CSTMS and incorporated within the ROMS sediment transport model (Warner et al., 2008). Finally, a numerical model of the Adriatic developed by Harris, R. Signell (US Geological Survey), and Chris Sherwood (US Geological Survey) (Harris et al., 2008; Sherwood et al., 2004) has been adopted by researchers from CNR-ISMAR (Consiglio Nazionale delle Ricerche, Istituto di Scienze Marine), Venice. They have used this model as both a research tool (Bignami et al., 2007) and to construct an operational model (Chiggiato and Oddo, 2006).

RELATED PROJECTS

In the past year, I have worked to publish findings funded as part of the EuroStrataform effort (Bever et al., in review; Harris et al., 2008). In revising Harris et al. [2008], we evaluated the degree to which the numerical model of suspended sediment transport for the Adriatic Sea matches observations. Calculations of suspended sediment concentrations compare very well to satellite images analyzed for January, 2003 (figure 5). Both show turbid waters recirculating in the northern Adriatic as part of a counter-clockwise gyre, and both resolve the structure of the Western Adriatic Coastal Current (WACC) which narrows as it progresses southward.

I helped to guide efforts by NOAA's GLERL in using a numerical model previously developed under ONR funding (Harris and Wiberg, 2001; Harris and Wiberg, 2002) to estimate sediment resuspension in Lake Michigan. Results from that study indicate that sediment availability and bottom texture are critical parameters in estimates of turbidity in the lake environment (Hawley et al., 2008).

As my project objectives are closely aligned with the NOPP CSTMS project, I attended CSTMS meetings in May and October, 2007. At these, I reviewed modeling techniques derived from earlier, ONR-funded efforts (see Harris et al., 2004; Harris and Wiberg, 2001), and updated the CSTMS community on progress made for this program. Efforts to account for near-bed stratification within three-dimensional models such as ROMS were especially encouraged at these meetings.

The gravity flow model of Harris et al. (2004; 2005), developed as part of StrataFORM has been useful to other projects. For example, Kniskern (2007) used the ECOM-SED version of this model to evaluate flood emplacement by the Waiapu River, North Island, New Zealand. The model has also been adopted to evaluate flood emplacement offshore of several rivers of the U.S. west coast by a group funded by the National Science Foundation (PIs include M. Goni, R. Wheatcroft, and J. Warrick). During the summer, 2008, a VIMS sponsored REU (Research Experience for Undergraduates) student used this model to evaluate dispersal of material from the Umpqua River, Oregon. She will present her results at the Fall, 2008 AGU meeting (Moriarty et al., 2008).

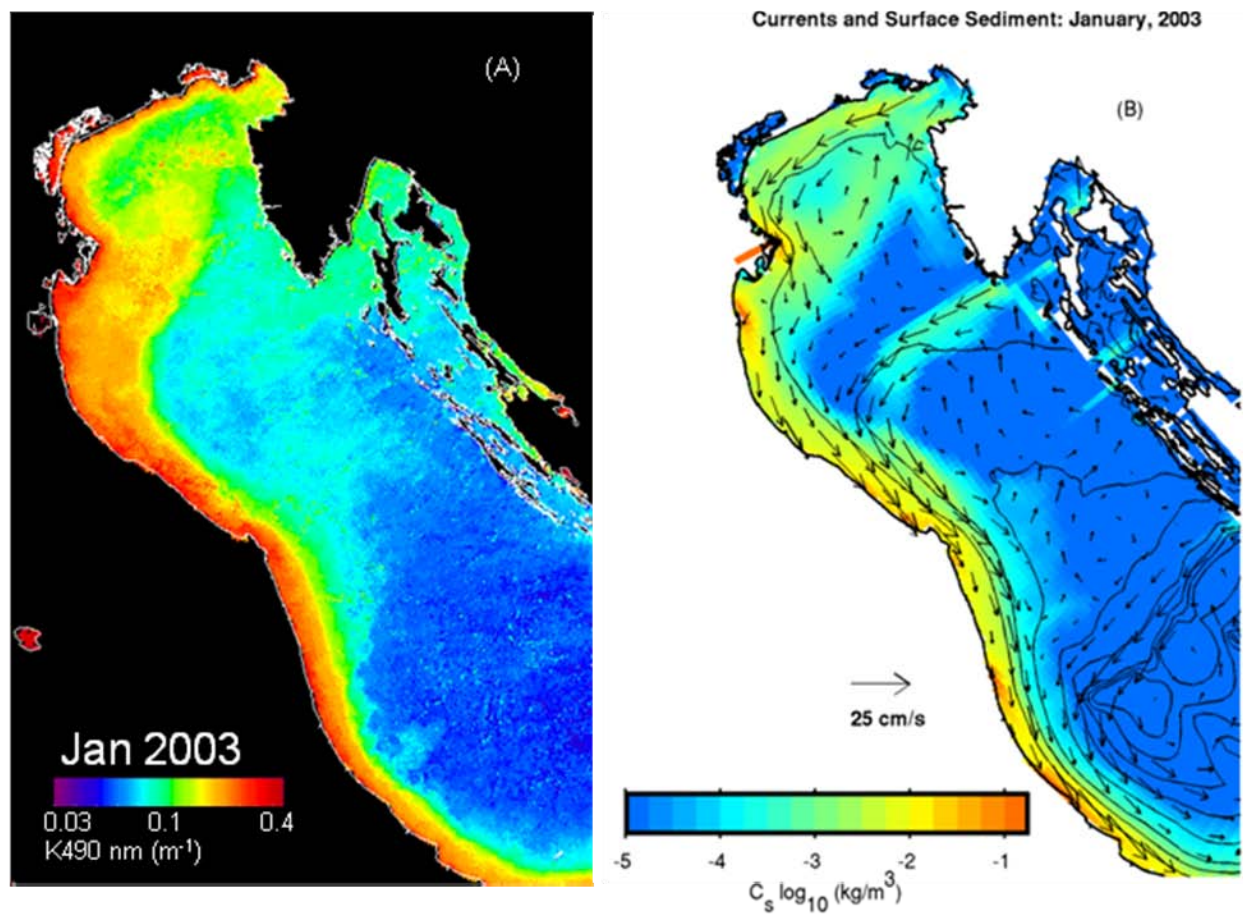


Figure 5: (A) Composite of satellite images from January, 2003. Extinction coefficient at 490 nm, K_{490} measured by MODIS on the NASA Aqua polar-orbiting satellite. Analyzed image supplied by E. Mauri, Remote Sensing Group, Istituto Nazionale di Oceanografia e Geofisica Sperimentale, Trieste, Italy. (B) Surface sediment concentration (color) and current velocities (arrows) estimated by Harris et al [2008], averaged for January, 2003.

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HONORS AND AWARDS

- Courtney Harris, Virginia Institute of Marine Sciences was named the “Alumni Memorial Term Distinguished Associate Professor” by the College of William and Mary for 2007 – 2010.